STRENGTHENING OF PRE-DAMAGED CONCRETE CYLINDERS USING POST-TENSIONED STEEL STRAPS

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Abstract

This article investigates the effectiveness of an innovative post-tensioned steel strapping strengthening solution at enhancing the behaviour of pre-damaged plain concrete cylinders. To achieve this, 24 Φ100×200 mm cylinders were subjected to axial compression. 18 of such specimens were initially tested to produce three different levels of damage. Subsequently, these pre-damaged specimens were repaired and then strengthened using different strap spacing and number of confining layers of straps. The results indicate that the post-tensioned steel straps were extremely effective at enhancing the strength of the pre-damaged specimens by up to 313%. The strapping also increased the axial deformability of pre-damaged cylinders to values of 2.64-2.95%. However, the effectiveness of the repair solution varied with the pre-damage level. This article contributes towards developing more rapid and effective strengthening solutions suitable for damaged reinforced concrete (RC) structures.

Keywords: Concrete structures; Columns; Compressive strength; Reinforcement; Testing, structural elements; Developing countries; Seismic engineering

INTRODUCTION

Recent destructive earthquakes in developing countries (e.g. Nepal 2015, Ecuador 2016, Mexico City 2017, Taiwan 2018) have caused extensive human and financial losses due to the inadequate behaviour of many existing reinforced concrete (RC) structures. Many collapses in these structures can be attributed to the local failure of structural components, which should (ideally) be strengthened to reduce the seismic vulnerability of the structures. However and due to financial constraints, in many developing countries, strengthening interventions are mainly carried out on structures damaged after an earthquake.

In order to reduce the risk of potential collapse and to allow access to rescue workers and first responders, earthquake-damaged structures need rapid strengthening interventions. This in turn requires readily available fast strengthening techniques that use simple tools, widely available materials and relatively low-skilled labour. Previous research has investigated the use of steel cages to strengthen RC columns (Sahoo and Rai 2009, Nagaprasad et al. 2009, Castro et al. 2018), although in general such cages only provide passive confinement. Recent research has verified the effectiveness of an innovative “active confining” technique at enhancing the capacity and deformability of concrete components (Ma et al. 2014; Garcia et al. 2015, Helal et al. 2016, Ma et al. 2016). The technique post-tensions high-strength steel straps around concrete members using air or hand-operated strapping tools as those utilised in the packaging industry (see hand tool in Figure 1a). Following the post-tensioning, the steel straps are clamped mechanically using clips to maintain the post-tensioning force (Figure 1b). Unlike other strengthening techniques (e.g. concrete/ferrocement jacketing, steel plates/tube jacketing, or FRP), the external strapping provides active confinement to the full cross-section of members, thus increasing their load and deformation capacity. Previous research has also verified the effectiveness of steel strapping confinement at enhancing the strength and deformation capacity of undamaged cylinders (Lee et al. 2014), but the technique has never been used to strengthen damaged concrete. It should be noted that, in actual strengthening interventions, most structures have some degree of damage (e.g. cracking) even under service conditions. Despite of this, only limited research has examined the behaviour of damaged NSC specimens confined with external FRP (Ilki and Kumbasar 2003, Liu et al. 2004, Peled 2007, Wu et al. 2014, Zhou et al. 2015), whereas only two studies have investigated the behaviour of pre-damaged cylinders strengthened with FRP jackets (e.g. Guo et al. 2016, Panjehpour et al 2016). The initial cost of FRP sheets may also prevent their use as a confining solution in many medium and low-income developing countries. As a consequence, alternative low-cost techniques for confining concrete are deemed necessary.

This article investigates experimentally the effectiveness of an innovative post-tensioned steel strapping technique as a repair/strengthening solution for pre-damaged concrete cylinders. The main parameters investigated include the level of pre-damage, as well as the strap spacing and number of confining layers of straps. The main objective of this study is to assess the effectiveness of the steel strapping confinement at increasing the axial strength and deformation capacity of pre-damaged cylinders. The outcomes of this article contribute towards developing faster and more effective strengthening solutions suitable for damaged concrete structures.

2. Experimental programme

2.1 Specimen characteristics and material properties

In this study, small pre-damaged cylinders are tested so as to provide an initial understanding of the levels of strength enhancement and axial deformation that can be achieved using different amounts of post-tensioned steel straps. A total of 24 concrete cylinders with diameter 100 mm and height 200 mm were cast using a single mix of Ordinary Portland cement (OPC), according to the proportions shown in Table 1. A water-cement ratio of 0.39 was chosen. River sand was used as fine aggregate, whereas crushed granite stone with maximum size of 10 mm was used as coarse aggregate. All specimens were cast at the same time and cured together in water for 28 days. The mean compressive concrete strength at 28 days (as obtained from nine 100×200 mm cylinders) was f_{co}=50.3 MPa with a standard deviation of 4.60 MPa.

Table 2 summarises the main characteristics of the tested specimens. In this table, the specimens are identified with an ID according to the concrete strength (Cylinder 50 MPa=C50), steel strap spacing (0, 10, or 30 mm), and number of strap layers (0, 1, 2 or 3). The last digit (between brackets) in the ID refers to the level of initial damage on the tested specimen (0 or undamaged, and pre-damage levels of +50, +100 and -50), as described in the following section. Table 2 also reports the repair and strengthening intervention carried out on each specimen and the amount of confinement.

After the initial tests, the surface of pre-damaged cylinders was treated with grout mortar to produce a smooth surface. The grout mortar was prepared in the laboratory with cement:sand:water proportions of 1:1:0.5. The external confinement used to strengthen the specimens consisted of high-strength steel straps with nominal cross section 0.5×15.9 mm. Table 3 shows the average mechanical properties of the straps obtained from three direct tension tests on coupons.

2.2 Test setup, instrumentation and pre-damage

All specimens were subjected to uniaxial monotonic compression using a universal testing machine with a maximum capacity of 2,500 kN. The tests were performed in displacement control using a constant rate of 0.01 mm/s. Before testing, the top and bottom of all cylinders were mechanically ground to produce a smooth surface, thus ensuring full contact of the loading platens during testing. The development of cracks was visually monitored during the tests so as to ensure that damage started by formation of vertical cracks at the mid-height of the specimens.

The axial strains of the specimens were measured using two PI displacement transducers with a 50 mm gauge length fixed vertically at both sides of the specimens. A single strain gauge located at the mid-height of the specimens monitored the strain of the confining steel straps. During the test, the axial load, vertical displacement, and lateral strains were recorded by an automatic data logger. Figure 2 shows a typical specimen during testing.

18 of the 24 cylinders were initially subjected to compressive load in unconfined conditions to produce a pre-damage level. It should be mentioned that to date there is no agreement on specific levels of pre-damage that can be used for testing pre-loaded specimens. Wu et al (2014) used pre-damage levels: +85%, +100%, -95%, -90%, -85%, -80%, -65% and -50% of f_{co}, where f_{co} is the peak compressive strength of unconfined control specimens, and where the positive sign indicates pre-

loading before reaching f_{co}. Ferroto et al. (2017) considered different pre-damage levels, i.e. low (+40 to +55% of f_{co}), medium (+60 to +70% of f_{co}) and high (+80 to +90% of f_{co}). More recently, Micelli et al. (2018) used levels of +20%, +50% and +80% of f_{co}. Accordingly, three pre-damage levels were selected (see also IDs in Table 2):

- Pre-peak (+50%): six cylinders initially tested up to a load equal to 50% of f_{co}, which is representative of moderate damage
- Peak (+100%): six cylinders tested at a load equal to f_{co}, or significant (repairable) damage, and
- Post-peak (-50%): six cylinders tested until the capacity dropped by 50% after f_{co}, which is representative of severe damage

The rest of the specimens were tested in undamaged conditions, and such cylinders are identified using a (0) last digit in the IDs shown in Table 2.

2.3 Surface grouting and steel strap strengthening

Following the initial tests, the surface of the pre-damaged specimens (cylinders +50, +100 and -50) was patched using grout mortar so as to achieve a smooth surface. This was necessary to ensure full contact of the confining straps against the concrete during the pre-tensioning operation. In actual strengthening of damaged RC structures, damaged elements may also require the preparation of concrete surfaces for the application of the steel strapping, but this will depend on the severity and location of damage. No epoxy-injection was done to repair internal cracking in the specimens.

After the grout set, 15 pre-damaged specimens were strengthened using post-tensioned steel straps. To maintain the post-tensioning force, the straps were fastened mechanically using self-regulated end clips secured with jaws. The post-tensioning force was applied using a manual strapping tool (Figure 1a), which led to an initial tensioning force in the straps of approximately 50% of their yield strength, as measured by strain gauges fixed on the straps. Figure 3a shows schematically the dimensions of the steel straps and the dimensions of the specimens, whilst Figure 3b shows typical specimens after the surface grouting and steel strapping intervention. Whilst some stress losses are expected in the straps due to friction between the straps and the concrete surface during the post-tensioning process, previous test results (Moghaddam et al. 2010) indicate that such losses are typically less than 10% of the initial stress.

In this study, the clear spacing between steel straps was set equal to 10 and 30 mm. The strengthened specimens were confined with 1, 2 or 3 layers of steel straps. The number and spacing of steel straps selected for these tests aimed to produce values of volumetric confinement ratios ρ_v ($\rho_v=V_s f_{ys}/V_c f_c$, where V_s and V_c are the volumes of straps and confined concrete, respectively, and f_{ys} is the yield strength of the straps) ranging from 0.27 to 0.96. In real strengthening interventions, the designer can select the volumetric ratio ρ_v by changing the strap spacing, number of strap layers, and/or mechanical properties of the straps. However, typical values of ρ_v for practical confining applications on elements range between 0.05 and 0.50 (Lee at al. 2014; Ma et al. 2014). Whilst higher values of ρ_v could be used to strengthen structures on-site, the amount of confinement that can be installed is limited by practical aspects such as a) the clear spacing between steel straps necessary to secure the metal clips using the jaws (minimum 2-3 mm), b) the number of strap layers than can be secured using a single metal clip (usually no more than two or three layers of straps), c) the yield strength of the steel straps, and d) the available type/size of strapping tools and jaws.

3. Experimental results and discussion

Table 4 summarises the ultimate axial strength f_{cu}, ultimate axial strain, the corresponding axial strength and strain enhancements of the tested specimens over their pre-damaged counterparts, as well as the axial strength and strain difference of the specimens over their undamaged counterparts (i.e. specimens (0)). In all cases, the variation in readings between the two vertical transducers was less than 10%, thus indicating that the specimens did not experience significant bending/leaning during the tests. However, several transducers failed prematurely during the tests due to concrete cracking beneath the gauge fixing points. As such, the values reported in the table were captured by one of the transducers that recorded the full test. Unfortunately, the gauges fixed on the steel straps did not record reliable values, and therefore these are not reported here. The following sections summarise the most significant observations of the testing programme and discuss the results listed in Table 4.

3.1 Failure Mode

As expected, the unconfined concrete specimens of each group failed in a sudden and explosive manner (cylinders C50-0-0 in Table 4). Conversely, all strengthened undamaged cylinders (0) failed gradually. The first load applied during the tests (strength <25% of f_{cu}) did not produce visible cracks on the specimens' surface. As the load increased, narrow vertical cracking was observed at the mid-height of the specimens. Such cracks extended towards the top and bottom of the cylinders when the load increased to approximately 50% of f_{cu}. As the load increased to 75%-100%f_{cu}, the steel straps at the cylinders' mid-height were clearly confining the specimens, as evidenced by popping sounds due to strap elongation. This was accompanied by 'flaking off' of concrete. As the test progressed, extensive cracks developed at the middle of the strengthened specimens. However, the confinement delayed the specimens' failure. Failure of cylinders (0) was dominated by sudden rupture of the steel strap (near the clip) at approximately the specimens' mid-height, followed by concrete crushing. Figure 4 shows typical failures of the strengthened undamaged cylinders (0).

The experimental observations indicate that the initial level of damage had a minor effect on the final failure mode of the pre-damaged specimens (+50), (+100) and (-50). Consequently, the following discussion is valid for the above three cylinder groups. Unlike cylinders (0), pre-existing vertical cracks were visible in all pre-damaged cylinders, although such cracks were covered by grout. At a stress of around 50% of f_{cu}, existing cracks started re-opening and further cracks formed towards the top and bottom of the cylinders. The steel straps delayed crack development and widening as the load increased to 50%-75%f_{cu}. A crushing sound was heard when the ultimate strength f_{cu} was approaching, but the specimens did not fail due to the confining pressure applied by the steel straps. Final failure was dominated by sudden rupture of the steel straps (near the clip) at the mid-height of the specimens, followed by concrete crushing. A visual examination after the tests revealed that, compared to cylinders (+50), the specimens with more pre-damage (+100 and -50) experienced less extensive cracking and concrete crushing during the tests in strengthened condition. This can be attributed to the fact that it takes less effort (energy) to widen the existing cracks produced during pre-damage than to develop new cracks during the test in strengthened conditions. Figure 5 shows typical failure modes of the above cylinders.

3.2 Axial stress-strain behaviour

Figure 6a-d shows the average axial stress-strain results of the tested specimens as measured by the vertical strain gauges. Unfortunately, some of the gauges detached prematurely as they were subjected to excessive compression and cracking. Consequently, the curves are only shown up to the point where both vertical gauges gave reliable readings.

The data in Table 4 show that, compared to the original strength of C50-0-0(0) (i.e. 52.8 MPa), the pre-damage reduced the strength of the unconfined cylinders C50-0-0(+50), C50-0-0(+100) and C50-0-0(-50) by 5%, 60%, and 64%, respectively. In Figure 6a-d, the sudden failure of the unconfined specimens is indicated by a circle.

The results in Figure 6a indicate that the undamaged strengthened cylinders (0) had higher strength compared to the unconfined specimen. As shown in Figure 6a and Table 4, ultimate strengths increased by up to 41% with reference to the control specimen C50-0-0(0). This can be attributed to the lateral (active) confining pressure provided by the steel straps, which restricted the cylinders' lateral dilation and delayed concrete cracking. It is also evident that cylinders with heavier confinement (e.g. see C50-30-3(0) and C50-10-2(0)) enhanced more the compressive strength than those with light confinement. Figure 6a also shows that the use of steel strapping confinement also increased the deformation capacity of the cylinders by up to 495% (C50-10-2(0)). Moreover, the use of external confinement led to a 'ductile' response, characterised by short plateaus after the elastic stage (e.g. see C50-10-2(0)).

The data in Figure 6b-d and Table 4 confirm that the steel strapping was very effective at restoring the strength of pre-damaged cylinders. Compared to the pre-damaged unconfined specimens, ultimate strength enhancements of up to 83%, 313% and 171% were observed in pre-damaged cylinders (+50), (+100) and (-50), respectively. However, unlike the undamaged specimens, the ultimate strength of pre-damaged cylinders increased with the confinement ratio. Overall, pre-damaged cylinders (+100) had the highest increase in strength (+235% on average), whereas cylinders in group (-50) had the highest axial strain enhancements (+220% on average). In general, the ultimate strains reported in Table 4 (in the range of 2.64-2.95%) are comparable to those mobilised in severely pre-damaged CFRP-confined cylinders (Guo et al. 2016). Figure 6b-d also show that the use of the steel straps led to a 'ductile' response, in particular for specimens with heavier confinement (e.g. C50-30-3(X) and C50-10-2(X)). As a result, the steel straps can be used instead of FRP in developing countries where the initial cost of FRP hinders rapid strengthening interventions after strong earthquakes.

Figure 6b-d also indicate that the steel strapping recovered some of the original stiffness of the pre-damaged specimens. However, such recovery is negligible if the concrete is previously crushed (see for instance Figure 6d). In spite of this, Figure 6d indicates that the steel strapping technique can be effectively used to strengthen even severely damage concrete.

3.3 Influence of confinement ratio on ultimate strength and deformation capacity

Figure 7a and b show, respectively, the ultimate strength and strain for the confining volumetric ratios ρ_v used on the tested cylinders. It is shown that, regardless of whether the cylinders were pre-damaged or not, both the strength and strain of the tested cylinders vary approximately linearly with ρ_v. The results also show that whilst pre-damaged cylinders (-50) had lower strength, they also had the highest deformation capacity. This behaviour was somehow expected as the low compressive strength and stiffness of heavily damaged concrete tend to make the concrete more 'ductile' than the original used for casting.

The results listed in Table 4 indicate that even a modest amount of confinement (ρ_v =0.27) is sufficient to recover the original strength of pre-damaged specimens C50-30-1(+50) and C50-30-1(+100). Conversely, heavy confinement (ρ_v=0.96) was necessary to recover the original strength of the severely damage cylinder C50-10-2(-50). It is also noted that cylinders with the same ρ_v in undamaged group (0) and pre-damaged group (+50) had similar strengths. Indeed, the axial strength difference of specimens in group (+50) is only -2% lower than that of group (0), whilst the average axial strain difference is +30%. This suggests that the initial damage imposed on the latter cylinders had a relatively minor influence on the strength results, but it did influence the axial strain capacities.

The results listed in Table 4 show that, compared to undamaged group (0), the steel straps recovered the strength of pre-damaged cylinders (+100) with heavier confinement (C50-30-2(+100), C50-30-3(+100) and C50-10-2(+100)) but not that of cylinders with light confinement. However, in all cases the strain capacity of group (+100) increased considerably (by up 43% for C50-10-1(+100)). The data also indicate that the technique did not restore the capacity of any of the specimens in group (-50), as all specimens had lower strength than their undamaged counterparts (-38% on average). In spite of this, the axial strain capacity was enhanced by an average of 86%, thus confirming the effectiveness of the strapping technique at enhancing concrete deformability.

The experimental observations also confirm that for approximately similar levels of confinement (ρ_v=0.48 and 0.53, which are typical levels of confinement achievable in practical strengthening applications) and regardless of whether cylinders were undamaged or pre-damaged, adding two strap layers at 30 mm (e.g. see all cylinders C50-30-2(X)) enhanced more the strength and deformability than adding one strap layer at 10 mm (cylinders C50-10-1(X)). From a practical point of view, this suggests that it is more effective to increase the amount of confinement by adding more layers of straps rather than by reducing the strap spacing. This in turn would also reduce the intervention time as fewer straps have to be post-tensioned and fewer clips need to be clamped. Therefore, it is suggested that practical strengthening applications of damaged RC cylinders are carried out using a minimum of two layers of post-tensioned steel straps.

Based on the results of this study, it is concluded that the post-tensioned steel strapping is a rapid and very effective strengthening solution to increase the strength and deformability of pre-damaged cylinders. Since the technique requires simple tools, widely available materials and relatively low-skilled labour, the steel strapping can be used for rapid strengthening of earthquake-damaged structures to allow access to rescue workers and first responders. However, due to the relatively limited number of specimens and confinement layouts, further tests are necessary to verify the initial findings and to assess the effectiveness of heavier confinement (ρ_v>1) in enhancing the strength and deformability of damaged elements. Moreover, as failure of the tested cylinders was dominated by rupture of the steel straps near the steel clips, more efficient clamping/anchoring solutions could be developed in future research. Future research should also investigate the effectiveness of the strapping technique on pre-damaged square/rectangular cylinders. It should be also noted that in many cases a combination of bending/axial loads or shear can lead to failures of RC elements during earthquakes, and therefore current research is investigating the use of post-tensioned steel strapping on larger pre-damaged columns with internal longitudinal/transversal bars. Research efforts are also addressing how to correlate the results from small cylinders (as those tested in this study) to larger specimens (including size effects), as well as to develop design/assessment models that can be included in strengthening guidelines.

4. Summary and conclusions

This article examined the effectiveness of an innovative post-tensioned steel strapping strengthening solution at enhancing the behaviour of pre-damaged concrete cylinders. 24 100×200 mm specimens were subjected to axial compression. 18 of such specimens were pre-damaged at moderate (+50), significant (+100) or severe (-50) levels, and were subsequently strengthened with steel straps using different confinement ratios. Based on the results of this study, the following conclusions can be drawn:

- Failure of unconfined concrete specimens was sudden and explosive. Conversely, the failure of specimens strengthened with heavier confining steel straps (e.g. specimens C50-30-3(X) and C50-10-2(X)) was ‘ductile’ and characterised by a plateau after the elastic stage.
- In comparison to pre-damaged unconfined specimens, the strength of pre-damaged cylinders (+50), (+100) and (-50) was enhanced by up to 83%, 313% and 171%, respectively. Moreover, pre-damaged strengthened cylinders developed significant axial deformations in the range of 2.64-2.95%. As expected, the use of heavy confinement (ρ_v>0.80) led to the best performance for all pre-damaged cylinders.
- The steel straps recovered the strength of pre-damaged specimens (+50) and (+100) with heavy confinement when compared to undamaged specimens (0). Conversely, the average strength of cylinders (-50) was -38% lower on average. However, axial strain capacity was enhanced by an average of 86% in the latter specimens.

- The results indicate that even modest confinement (ρ_v=0.27) recovered the original strength of specimens with moderate (cylinders (+50)) or significant pre-damage (cylinders (+100)). However, heavy confinement (ρ_v=0.96) was necessary to recover the original strength of severely damage cylinders (cylinders (-50)).
- The experimental data indicate that, from a practical point of view, it is more effective to increase the amount of confinement (ρ_v) by adding more layers of straps rather than by reducing the strap spacing. It is also suggested that practical strengthening applications of damaged RC cylinders are carried out using a minimum of two layers of post-tensioned steel straps.
- Overall, the rapid steel strapping technique can be used to strengthen even severely damage concrete. However, as failure of the tested cylinders was dominated by rupture of the steel straps near the clips, more efficient clamping/anchoring solutions could be developed in future research. Moreover, due to the relatively limited number of specimens and confinement layouts used in the study, further tests are necessary to confirm the initial findings presented here.

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Table 5. Mix portions for $1m^3$ of concrete

Material	**Amount**
OPC (kg)	409
Sand (kg)	806
Gravel (kg)	1025
Glenium C380 superplasticizer (*l*)	16
Water (kg)	162

Table 6. General characteristics of tested specimens

Specimen ID	Steel straps layers	Spacing (mm)	Pre-damage level (%)	Confining volumetric ratio, ρ_v	Repairing/ Strengthening
C50-0-0(0)	-	-	-	0	None
C50-30-1(0)	1	30	-	0.27	Steel strapping
C50-10-1(0)	1	10	-	0.48	Steel strapping
C50-30-2(0)	2	30	-	0.53	Steel strapping
C50-30-3(0)	3	30	-	0.80	Steel strapping
C50-10-2(0)	2	10	-	0.96	Steel strapping
C50-0-0(+50)	-	-	+50	0	Surface grouting
C50-30-1(+50)	1	30	+50	0.27	Surface grouting + steel strapping
C50-10-1(+50)	1	10	+50	0.48	Surface grouting + steel strapping
C50-30-2(+50)	2	30	+50	0.53	Surface grouting + steel strapping
C50-30-3(+50)	3	30	+50	0.80	Surface grouting + steel strapping
C50-10-2(+50)	2	10	+50	0.96	Surface grouting + steel strapping
C50-0-0(+100)	-	-	+100	0	Surface grouting
C50-30-1(+100)	1	30	+100	0.27	Surface grouting + steel strapping
C50-10-1(+100)	1	10	+100	0.48	Surface grouting + steel strapping
C50-30-2(+100)	2	30	+100	0.53	Surface grouting + steel strapping
C50-30-3(+100)	3	30	+100	0.80	Surface grouting + steel strapping
C50-10-2(+100)	2	10	+100	0.96	Surface grouting + steel strapping
C50-0-0(-50)	-	-	-50	0	Surface grouting
C50-30-1(-50)	1	30	-50	0.27	Surface grouting + steel strapping
C50-10-1(-50)	1	10	-50	0.48	Surface grouting + steel strapping
C50-30-2(-50)	2	30	-50	0.53	Surface grouting + steel strapping
C50-30-3(-50)	3	30	-50	0.80	Surface grouting + steel strapping
C50-10-2(-50)	2	10	-50	0.96	Surface grouting + steel strapping

Table 7. Properties of steel straps used for confinement

Properties	Description
Width	15.9 mm
Thickness	0.5 mm
Yield stress	810 MPa
Yield strain	0.006
Ultimate stress	950 MPa
Strain at failure	0.014
Elastic modulus	3.2 GPa

Table 8. General results of tested specimens

Specimen ID	Ultimate axial strength f_{cu} (MPa)	Ultimate axial strain (%)	Axial strength enhancement over pre-damaged (%)	Axial strain enhancement over pre-damaged (%)	Axial strength difference over undamaged (%)	Axial strain difference over undamaged (%)
C50-0-0(0)	52.8	0.40	-	-	-	-
C50-30-1(0)	57.5	0.60	+9	+50	-	-
C50-10-1(0)	66.3	0.63	+26	+58	-	-
C50-30-2(0)	68.8	0.88	+30	+120	-	-
C50-30-3(0)	67.9	1.40	+29	+250	-	-
C50-10-2(0)	74.2	2.38	+41	+495	-	-
C50-0-0(+50)	50.2	0.46	-	-	-	-
C50-30-1(+50)	53.6	0.69	+7	+50	-7%	+15%
C50-10-1(+50)	53.5	0.85	+7	+85	-19%	+35%
C50-30-2(+50)	63.9	1.50	+27	+226	-7%	+70%
C50-30-3(+50)	66.4	1.63	+32	+254	-2%	+16%
C50-10-2(+50)	91.8	2.64	+83	+474	+24%	+11%
C50-0-0(+100)	20.7	0.52	-	-	-	-
C50-30-1(+100)	50.2	0.76	+143	+46	-13%	+27%
C50-10-1(+100)	62.8	0.90	+203	+73	-5%	+43%
C50-30-2(+100)	73.9	1.24	+257	+138	+7%	+41%
C50-30-3(+100)	75.3	1.55	+264	+198	+11%	+11%
C50-10-2(+100)	85.5	2.71	+313	+421	+15%	+14%
C50-0-0(-50)	19.0	0.61	-	-	-	-
C50-30-1(-50)	28.3	0.75	+49	+23	-51%	+25%
C50-10-1(-50)	46.6	1.61	+145	+164	-30%	+156%
C50-30-2(-50)	41.8	2.42	+120	+297	-39%	+175%
C50-30-3(-50)	41.2	2.12	+117	+248	-39%	+51%
C50-10-2(-50)	51.5	2.95	+171	+384	-31%	+24%

Figure 1 (a) Tensioning tool, and (b) steel straps with self-regulated end clips

Figure 2 Test setup of axial compression test

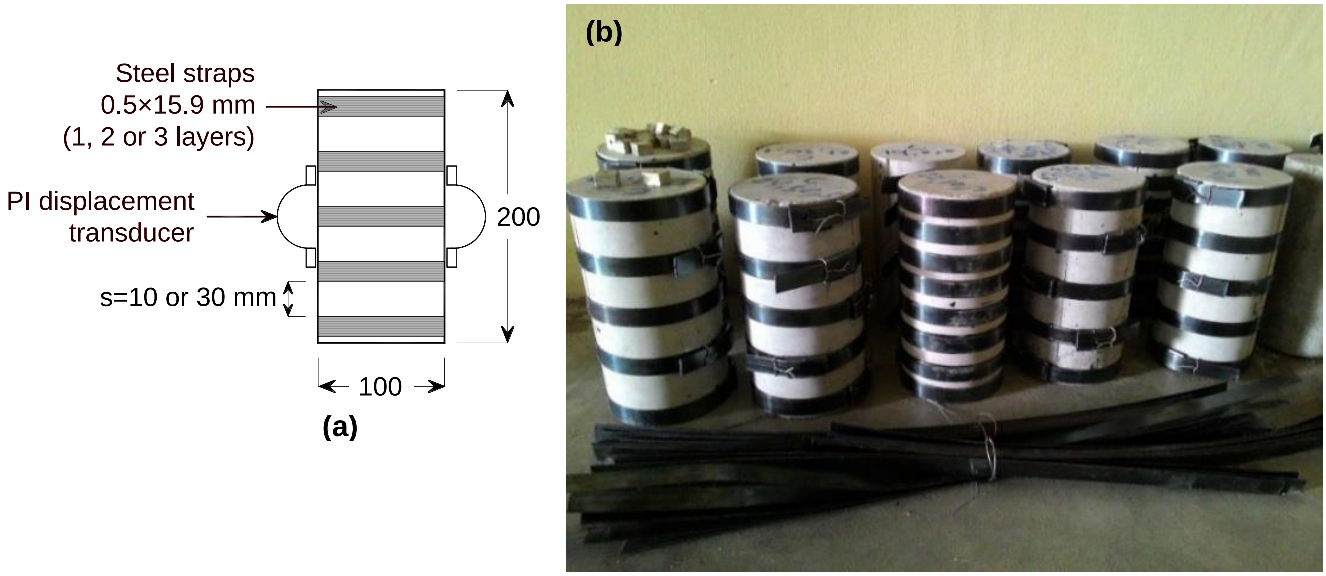

Figure 3 (a) Dimensions of steel straps and of tested specimens, and (b) typical specimens after surface grouting and steel strapping

Figure 4 Typical failure modes of strengthened cylinders in columns (0)

(a) C50-10-1(-50) (b) C50-10-1(+50) (c) C50-10-1(+100)

Figure 5 Typical failure mode of pre-damaged strengthened columns

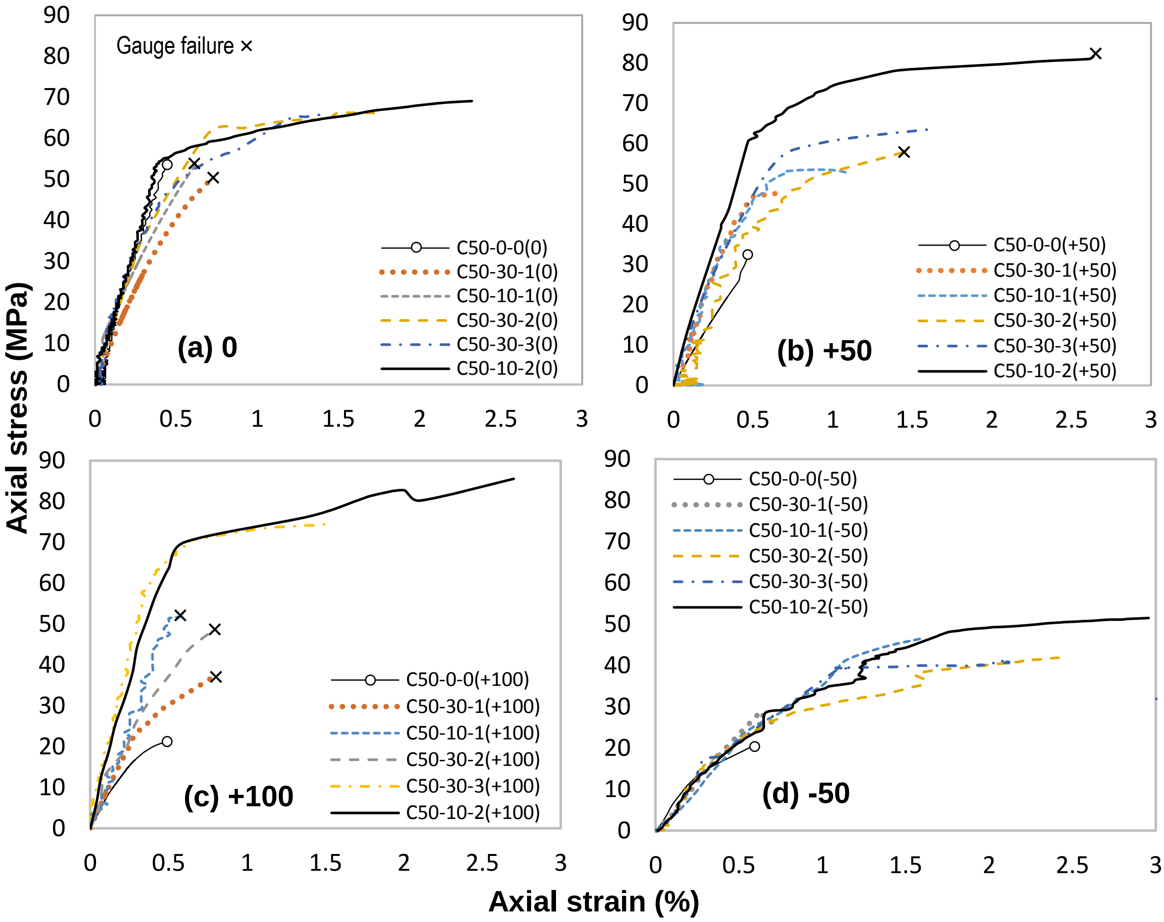

Figure 6 Stress-strain relationships of tested specimens

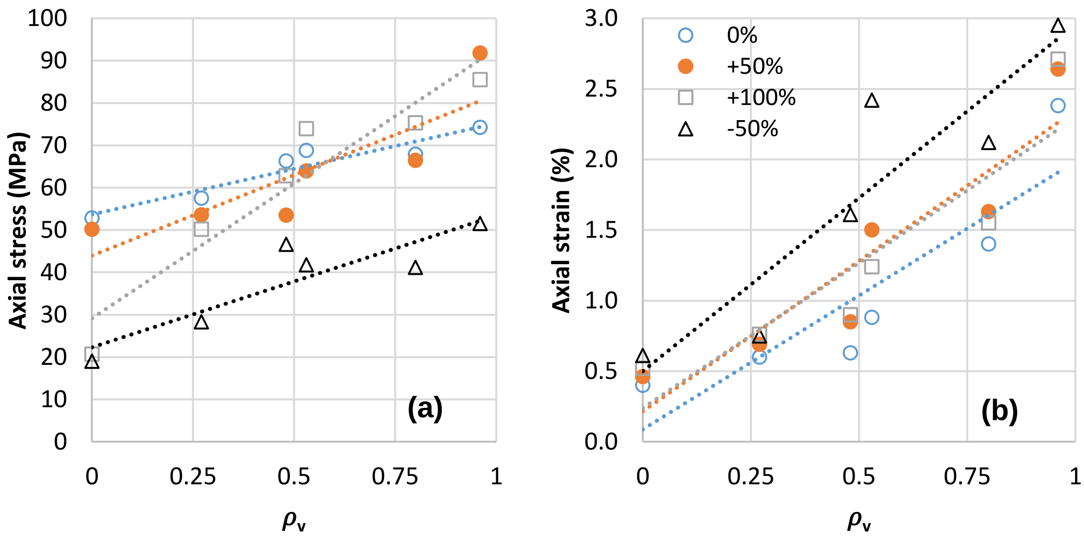

Figure 7 Effect of confining volumetric ratio on (a) axial strength and (b) axial strain